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FEASIBILITY OF USING HIGH TEMPERATURE SUPERCONDUCTING
MAGNETS AND CONVENTIONAL MAGNETIC LOOP ANTENNAS
TO ATTRACT OR REPEL OBJECTS AT THE
SPACE STATION

Final Report

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ABSTRACT

A study was undertaken to see if magnetic forces can be used at the Space Station to attract or repel spacecrafts such as the Orbital Manuevering Vehicle (OMV) or the Orbiter. A large magnet, in the form of a current loop, is assumed to be placed at the Space Station and another one on the spacecraft. The expression for the force between the two dipoles (loops) is obtained. Using a force of 15 Newtons (3.4 pounds) in order to move the spacecraft, the number of ampere-turn needed in the current loops was calculated at various distances between them.

The expression for the force of attraction between a current loop and a soft magnetic material was also examined and the number of amp-turn needed to provide a force of one-tenth of a pound at various distances is also calculated. This one tenth of a pound force would be used in a life line system for the retrieval of an adrift crewman or tool at the Space Station.

The feasibility of using conventional antenna on the Station and the incoming vehicle for attraction or repulsion was also examined.

INTRODUCTION

In the earth environment, strong magnetic forces are needed at short distances for attraction or repulsion, while in space, weak forces are needed at large distances due to the microgravity environment. The force needed to move an Orbital Maneuvering Vehicle (OMV), weighing 20,000 pounds, with an acceleration of $150 \mu g$ at low earth orbit will be about 3 pounds, while a force of 3.4 pounds (15 Newtons) will move the Orbiter (weighting 225,000 pounds) with $15 \mu g$ of acceleration. These are very small forces. A study was undertaken to examine if a force of about 3 pounds at a distance of approximately 100 feet, the distance of the object to be attracted to the Space Station, could be exerted using magnetic loop antennas, conventional electromagnets, or superconducting magnets. The temperature in the Space Station, due to background radiation, is about $100^\circ K$ which is below the critical temperature of the recently discovered high temperature superconductors (HTSC). Provided there is sufficient shielding from the sun, the HTSC could be used in the Space Station environment and could use cryogen (liquid hydrogen and oxygen) already aboard the Space Station for cooling.

Another problem examined was the retrieval of a drifting crewmember using a life line technique. With this technique, the crewmember shoots a small iron ball or plate with a monofilament line attached to it, at an energized electromagnet in the Space Station using a spring action gun. The magnet attracts the iron material as it gets closer and holds it. The crewmember then uses the line to move to the Station. The same technique could be used to retrieve a drifting tool.

MAGNETIC FIELDS AND FORCES

Magnetic Field Due to A Dipole

The magnetic flux density due to a magnetic pole of strength 'm' at a distance r is given by

$$B = \frac{\mu_0}{4\pi} \frac{m}{r^2} \quad (1)$$

where

$$\mu_0 = 4\pi \times 10^{-7}$$

and has the units T.m/A or N/A² or W/A.m,

where T stands for Tesla or Weber/m² and N for Newton. The pole strength 'm' has units of ampere-meter (A.m.). The force on a magnetic pole of strength 'm' placed in the magnetic field is given by

$$F = m B \quad (2)$$

The flux density at a distance much larger than the length of a dipole along its axis is given by

$$B = \frac{\mu_0}{4\pi} \frac{2M}{r^3} \quad (3)$$

where M is the magnetic moment of the dipole given by the product of its pole strength and length.

Force Between Two Dipoles

The potential energy of a dipole placed in the B field of another dipole is given by

$$U = -\vec{M} \cdot \vec{B} \quad (4)$$

The translational force acting on the dipole is,

$$F = -\nabla U = \vec{M} \cdot \nabla \vec{B} \quad (5)$$

In a uniform B field, there is no net translational force on a dipole as the gradient of B is zero.

Using (3) in (5) we get

$$F \simeq - \frac{\mu_0}{4\pi} \frac{6 M_1 M_2}{r^4} \quad (6)$$

The negative sign in (6) indicates force of attraction.

Field Due to A Current Loop on Its Axis

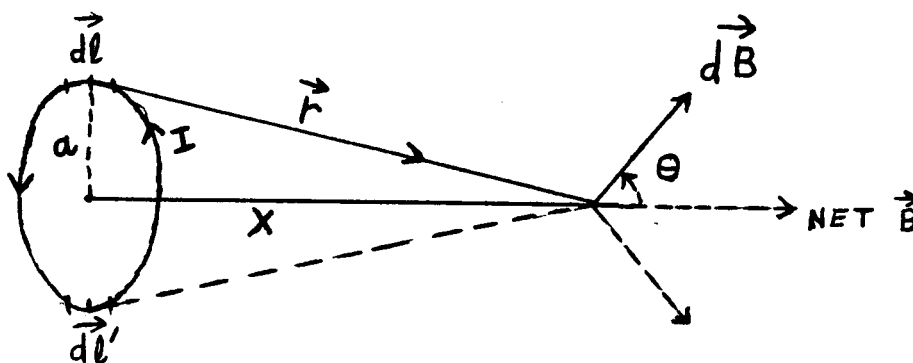


Figure 1.- Field On The Axis Of The Loop

The flux density at a point on the loop axis due to an element of length dl carrying current I is given by ⁴,

$$\vec{dB} = \frac{\mu_0}{4\pi} \frac{I \vec{dl} \times \hat{r}}{r^2} \quad (7)$$

where \hat{r} is unit vector along \vec{r} . The field is normal to the vector \vec{r} and element $d\vec{l}$.

The direction of field due to element $d\vec{l}$ diametrically opposite to $d\vec{l}$ is shown. The components of the field at right angles to the axis cancel, while along the axis they add.

The net field along the axis due to a loop with N turns is

$$\begin{aligned} B &= \int dB \cos \theta = \frac{\mu_0}{4\pi} \frac{IN \cos \theta}{r^2} \int_0^{2\pi a} dl \\ &= \frac{\mu_0}{4\pi} \frac{2INA}{(a^2 + x^2)^{3/2}} \quad (8) \end{aligned}$$

for $x \gg a$

$$B = \frac{\mu_0}{4\pi} \frac{2M}{x^3} \quad (9)$$

where $M = I N A$ (10)

and has a direction given by right hand cork screw rule.

Comparison of (3) and (9) indicates that a current loop is equivalent to a magnetic dipole with its magnetic moment given by (10).

Force Between Two Current Loops

Let the magnetic moments of two loops be equal, that is,
 $M_1 = M_2 = I N A$.

If the two loops, each having a cross section area of $1m^2$, are separated by a distance r along their common axis, then the force between the two loops using (6) is given by

$$F = \frac{\mu_0}{4\pi} \frac{6(IN)^2}{r^4}$$

which can be written in the form

$$IN = \sqrt{\frac{4\pi F r^4}{6\mu_0}} \quad (11)$$

A force of 15 Newtons (3.4 pounds) will move the OMV (weighing 20,000 pounds) with an acceleration of $150 \mu g$ and the Orbiter (weighing 225,000 pounds) with an acceleration of about $15 \mu g$. The values of ampere-turns (IN) needed to provide a force of 15 Newtons between the two loops at various distances are calculated from (11) and the results are shown in Table 1. The values of ampere-turns needed at distances of 0.1m, 10m, and 30m are 50, 5×10^5 , and 4.5×10^6 , respectively, and they will generate a field of $80 \mu T$, 0.8 T, and 7.2 T, respectively, at the center of the loops.

TABLE 1.- DISTANCE VERSES AMP-TURN VALUES

r(m)	0.1	1.0	5.0	10	15	20	25	30
I N (Amp-Turn)	50	5×10^3	1.25×10^5	5×10^5	1.12×10^6	2×10^6	3.1×10^6	4.5×10^6

Torque on A Current Loop in A Uniform Field

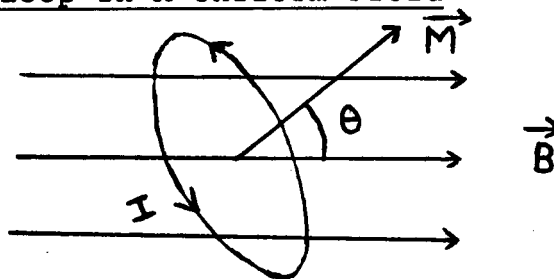


Figure 2.- Current Loop In A Uniform B Field

The torque acting on a current loop or a dipole placed in a uniform B field is given by ^{3,6}

$$\vec{T} = \vec{M} \times \vec{B} \quad (12)$$

There will be a torque acting on the current loop due to the earth's magnetic field causing the loop to precess about the earth's field. The torque acting on the loop (1m^2) with 10^6 ampere-turn will have a maximum value of 35 N.m. If the loop is fixed in the spacecraft, then the spacecraft will precess about earth's field. This problem may be overcome by firing jets in the spacecraft that impart equal and opposite torque. Another solution to the problem of a single dipole in precessing in the earth's field is to use two dipoles with oppositely directed magnetic moment vectors (i.e., quadrupoles), such that the torques due to earth's field cancel out.

Field Due to A Quadrupole

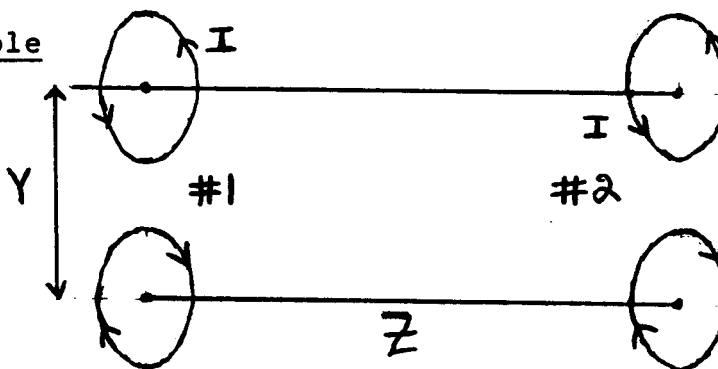


Figure 3.- Two Quadrupoles Separated By Z

The force that a quadrupole, consisting of a pair of current loops (with oppositely directed M vectors), separated by a distance Y, exerts on another quadrupole at a distance Z away is given by ⁵

$$F \approx \frac{\mu_0}{4\pi} \frac{18 M_1 M_2 Y^2}{Z^6} \quad (13)$$

for $Z \gg Y$.

where M_1 is the magnetic moment of each of the dipoles in the quadrupole #1 and M_2 is corresponding value for quadrupole #2.

This configuration requires 4×10^7 ampere-turn in each of the four loops to generate a force of 15 Newtons at a separation of 30 meters between the two quadrupole and at a separation of 1 meter between the two loops of each of the quadrupoles. Thus, there is a high price to pay in going from dipole to a quadrupole system in terms of size and ampere-turns needed.

Force Between Current Loop and A Piece of Magnetic Material at A Distance

The force on a ferromagnetic material placed in the B field is given by

$$F = \vec{M} \cdot \vec{\nabla} B \quad (14)$$

where M is the induced magnetic moment of the magnetic material given by

$$M = \sigma V \quad (15)$$

σ is the induced magnetization in the magnetic material of Volume V.

In ferromagnetic material ¹

$$B = \mu_0 (H + \sigma) \quad (16)$$

also

$$B = \mu_r \mu_0 H \quad (17)$$

where μ_r is the relative permeability of the ferromagnetic alloy.

Since $\mu_r \gg 1$, then

$$\sigma \simeq B/\mu_0 \quad (18)$$

The force of attraction between the current loop and the ferromagnetic alloy piece can be written using equations (14), (15), (18), and (9).

$$F = - \frac{3\mu_r\mu_0}{4\pi^2} \frac{M^2 V}{r^7} \quad (19)$$

The force of attraction between a magnet and magnetic material decreases inversely as the seventh power of the distance.

$M = I N A$ = magnetic moment of the loop and $V = A_2 \delta X$, where δX is thickness of the iron plate.

For a current loop ($1m^2$) and a ferromagnetic alloy plate ($4" \times 4" \times 1/8"$) with $\mu_r = 10,000$, the number of ampere-turns needed in the loop to produce an attractive force of one-tenth of a pound was calculated at various distances. The results obtained indicated values of 5.6×10^3 , 1.56×10^6 , and 1.77×10^7 ampere-turns at distances of 1m, 5m, and 10m, respectively.

When the magnet is in contact with the magnetic material, the force of attraction is given by

$$F = B^2 A / 2\mu_0 \quad \text{Newtons}$$

where A is the contact area and B is the flux density in the slight air-gap between the magnet and magnetic material. If $B = 1.0 \text{ Weber/m}^2$, then $F = 4 \times 10^5 \text{ Newtons/m}^2$ or 58.0 pounds/in^2 .

Weight of the Coil in the Current Loop

For ampere-turn value of 2×10^6 which will be needed to exert a force of 15 Newtons at 20m between the two current loops as well as between a current loop and sheet of ferromagnetic alloy at a distance of about 7m, let I be 10^4 amps and $N = 200$ turns. Assuming $J_c = 10,000 \text{ Amp/cm}^2$ (projected value) in the high temperature superconductor (HTSC): Crosssectional

area of the wire needed, $A = I/J_c = 1 \text{ cm}^2$

length of the wire in the loop $= \pi d N$

Volume of the coil $= \text{area} \times \text{length} = 62.83 \times 10^{-3} \text{ m}^3$

Weight of the coil $= \text{density} \times \text{volume} = 440 \text{ Kgms} = 970 \text{ pounds}$
 The density value chosen is the average of cladding material and the superconductor density (7000 Kgms/m^3). Length of the loop $= \text{wire diameter} \times N$
 $= \sqrt{\frac{4A}{\pi}} \times N = 11.3 \times 10^{-3} \times 200 = 2.26 \text{ meters.}$

The length of the loop could be reduced by increasing the number of layers of the coil. To make a solenoid, the superconductor needs to be copper stabilized in order to conduct the heat in case of a quench (the superconductor turning normal). The weight of the magnet will be 3-4 times the weight of superconducting coil.

Radiation Field of A Magnetic Loop Antenna

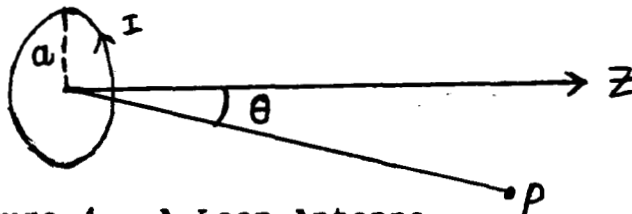


Figure 4.- A Loop Antenna

Let the normal to the plane of the loop of radius a be the z -axis. The radiated H field due to small loop ($a < \lambda/6$) at a point is given by

$$H_{\theta} = \frac{\pi N A I \sin \theta}{\lambda^2 r} \quad (20)$$

Using a phase locked loop in the incoming vehicle, the current in the second magnetic loop in the vehicle is kept in phase with the B field radiated by the first loop on the Station. The force on the second loop due to B field of the first loop antenna is

$$F = \vec{M}_2 \cdot \vec{\nabla} B$$

If $\theta = 90^\circ$, then

$$F = \frac{\mu_0 \pi N_1 I_1 A_1 N_2 I_2 A_2}{r^2 \lambda^2} \quad (21)$$

assuming $A_1 = A_2 = 1\text{m}^2$, and $I_1 N_1 = I_2 N_2 = I N$, the equation (21) yields

$$I N = \frac{\lambda r}{2\pi} \times 10^3 \sqrt{10F} \quad (22)$$

A force of 15 Newtons at a 30m separation between the two antennas will require 44×10^7 and 44×10^4 amp-turns at frequencies of 40 KHz and 40 MHz, respectively. The high value of amp-turns needed will require the use of superconducting loop. However, the eddy current losses at high frequency in superconductor will produce enough heat to render it normal.

The inductance of the loop coil is given by ¹⁰

$$L = \mu_0 N b \log(b/a) \quad (23)$$

where b and a are loop and wire radii, respectively. The reactance of the loop coil (ωL) will be too high to achieve the required amp-turns with a moderate sized signal generator.

DISCUSSION

The recently discovered HTSC with critical temperature above 100°K have a demonstrated ability to remain superconducting in magnetic field of at least 30 Teslas. A review of high-field and high-temperature superconductors appeared in references 12-15. At present, the current density of bulk HTSC material is about 1000 amp/cm² but work is being done to increase it substantially by improving the material fabrication and processing techniques. The weight of superconducting coil in the current loop was calculated with a projected current density of 10,000 amp/cm²; however, if the current density of the bulk HTSC material could be increased to 100,000 amps/cm², the weight of the superconducting coil would reduce to one-tenth of the calculated value. The current density of the thin film HTSC is about one million amp/cm². This high value makes one optimistic about reaching the goal for bulk material current density mentioned above.

In addition to the coil, a HTSC cylinder weighing about 20 pounds that can trap magnetic flux due to the Variant Incomplete Meisner Effect (VIME) can be used as a permanent magnet for fields up to 2.5 Teslas⁵. To make a permanent magnet cylinder using VIME, the HTSC cylinder is placed in the

magnetic field at $T > T_c$. Then the temperature of the cylinder is lowered below its T_c and the flux gets trapped in it, making it a permanent magnet, as long as $T < T_c$. In case the HTSC cylinder becomes normal and loses its magnetism, a magnetizing coil can be wound around to remagnetize it.

The use of conventional magnetic loop antennas with phase locked loop to provide a force of 15 Newtons at 30m distance was examined. It was concluded that due to inductance of the loop coil (0.2 mH for air core), the required value for ampere-turns would not be obtained with moderate sized signal generators.

To retrieve an adrift crewman, use of life line technique is proposed. The crewman would use a spring action gun that releases an iron ball or plate with a monofilament line attached to it towards a current loop that has been energized or towards the HTSC permanent magnetic cylinder in the Space Station. The iron ball or plate will be attracted to the loop or the magnet as it gets closer and will be held by it. Using the life line, the adrift crewmember will reach the Station. The 2.5 Tesla HTSC permanent magnet or loop with 2×10^6 amp-turns will be able to attract magnetic alloy plate (4" x 4" x 1/8") from a distance of 15-20 feet. The life line technique could be used to retrieve a tool that is drifting away. The crewmember will shoot a small permanent magnet at the tool with a line attached to it. The magnet will attach itself to the tool which can be pulled back using the line.

Jet propulsion will leave a lot of undesirable plumes hitting the Space Station when a spacecraft undocks from the Station. The ampere-turns needed to exert a repulsive force of about 3 pounds between the two current loops, one placed in the Space Station and the other in the spacecraft, will be 50 , 5×10^3 , and 1.25×10^5 at a distance of 0.1m, 1m, and 5m, respectively. The size of the current loops needed to provide the necessary force is not very large.

CONCLUSIONS

Current loops using the HTSC can be used to attract OMV or Orbiter with a force of 3 pounds at a distance of about 100 feet, although the size of the loop and the magnet is fairly large. With advances in material processing of HTSC, the current density could increase in the near future to a value that would reduce the size and weight of loop magnet substantially. A series of HTSC permanent magnets employing VIME could be used in place of loop magnets. Conventional magnetic loop antennas can not be used due to high reactance of

the loop at radiating frequencies. A life line technique could be used to rescue an adrift crewmember or tool in the early stages.

The size of the current loops needed for undocking a spacecraft from the Space Station is not very large. For undocking, magnetic repulsion would be used initially to move the spacecraft a few meters from the Station and then the jet propulsion resumed. This overcomes the problem of undesirable jet plumes hitting the Station.

Conventional magnets yielding field of several Teslas, such as a Bitter magnet cannot be used for space environment as the amount of power consumed by them is very large. The field of a Bitter magnet is given by ¹⁶

$$B \approx 11 \sqrt{W/r} \quad \text{Teslas}$$

where W is the power consumed in megawatts and r is the radius of solenoid in cms. To produce a field of 11 Teslas with a conventional Bitter magnet with a bore size of 4 cms, will require consumption of two megawatts of power!

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